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WADC TECHNICAL REPORT 57-353
PART IV

SOUND PROPAGATION NEAR THE EARTH'S SURFACE AS INFLUENCED BY WEATHER CONDITIONS

H. J. Sabine

Armour Research Foundation

JANUARY 1961

Contract No. AF 33(616)-5091

WRIGHT AIR DEVELOPMENT DIVISION

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BIOMEDICAL LABORATORY
AEROSPACE MEDICAL DIVISION
WRIGHT AIR DEVELOPMENT DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This report was prepared by the Armour Research Foundation of Illinois Institute of Technology under Contract No. AF 33(616)-5091 for the Aerospace Medical Division, Wright Air Development Division,* Wright-Patterson Air Force Base, Ohio. The work was in support of Project No. 7210, "Generation, Propagation, Action, and Control of Acoustic Energy," Task No. 71709, "Experimental Studies of Acoustic Energy Generation and Propagation." Technical supervision of the research program was the responsibility of Dr. Henning E. von Gierke and John N. Cole of the Bioacoustics Branch, Biomedical Laboratory, Aerospace Medical Division.

The work was carried out by H. J. Sabine, under the supervision of M. D. Burkhard.

* Wright Air Development Division was formerly Wright Air Development Center (WADC).

ABSTRACT

This report outlines engineering procedures for estimating the atmospheric attenuation of sound propagated from an elevated source to ground as a function of distance, source elevation angle, and meteorological data of the type which would be obtained routinely at an air or missile base. These procedures are based on the results of an experimental program, as reported in Parts I, II, and III, which covered distances up to 4 miles and source altitudes up to 14,000 feet.

PUBLICATION REVIEW

E. L. de Wilton

E. L. de WILTON, Capt., MC, USN
Acting Chief, Biomedical Laboratory
Aerospace Medical Division

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SECTION I

INTRODUCTION

One of the problems encountered in the operation of air and missile bases is that of community annoyance due to noise. This is becoming increasingly serious with the development of high-power rockets, whose noise output during launch is high enough to be disturbing over distances of many miles. An important factor in predicting noise levels in the vicinity of an air base or a launch site is knowledge of the sound-propagation characteristics of the atmosphere and their variation with weather conditions. This has been the subject of an extensive experimental study, as described in Parts I and II, in which attenuation from an airborne source to ground was measured as a function of source elevation from 2^{o} to 90^{o} for a large number of weather conditions. These measurements covered a horizontal range of 2 miles, and extended to an altitude of 4800 feet. In Part III, a theoretical analysis was made of the effect of meteorological factors on large-scale sound propagation over distances up to 15 miles and from source altitudes up to 80,000 feet. These ranges were estimated as the maximum over which the noise of the largest rocket launchings would cause community annoyance. Limited experimental data were presented for ranges up to 4 miles and source altitudes up to 14,000 feet.

In this report, the previous work is summarized in the form of engineering procedures to be used for estimating atmospheric attenuation in octave frequency bands as a function of: (1) distance from an elevated source to a ground observation point, (2) source elevation angle, and (3) meteorological data of the type which would be obtained routinely at an air or missile base.

Manuscript released by the author September 1959 for publication as a WADC Technical Report.

SECTION II

PREDICTION PROCEDURE

In predicting the noise level which will exist at a given location on the ground due to an airborne source such as an airplane or a rocket, it is necessary to know:

(1) the sound pressure level at a known reference distance from the source,

(2) the distance from the source to the point of observation on the ground, and

(3) the sound-propagation characteristics of the atmosphere along the path between the source and the ground point.

The reference sound pressure level is measured at a point close enough to the source that variations in atmospheric propagation are negligible, but far enough away that the sound output may be considered as concentrated at a point. Reference distances of 50 to 300 feet generally meet these requirements for most types of noise source. The reference sound pressure level should be measured as a function of frequency by suitable band analysis, and orientation of angle with respect to the axis of the source. If measurements of the reference level are made under different conditions than will occur when the source is airborne, an estimate of the resulting difference in reference level should be made and a corresponding correction applied. For example, if the measurements are made with the source on the ground, the reflection, assuming the ground is fairly hard, will result in a level 3 db higher than would be measured at the same distance with the source and receiver far removed from any reflecting surface. However, the reference level including ground reflection may be taken as the correct value, because the level observed on the ground when the source is airborne will be increased a similar amount by ground reflection. The predicted sound pressure level, SPL, on the ground due to the airborne source is given by:

$$SPL = SPL_o - 20 \log \frac{d}{d_o} - A \quad \text{db re } .0002 \text{ dynes/cm}^2 \qquad (1)$$

where

SPL_o = reference sound pressure level, db

d_o = distance from source at which reference level is measured

d = distance from source to observation point on ground

A = atmospheric attenuation, db, over distance $d - d_o$.

The reference level, SPL_o, is that measured or estimated along the line of sound propagation from the source to the ground observation point and will depend on the directional characteristics of the source output with respect to that line.

If measured data is not available, the reference sound pressure level, SPL_o, may be computed from known values of the sound power level and the directivity index of the source along the line of sound propagation to the ground observation point, using the relation:

$$SPL_o = PWL + DI(\theta) - 20 \log d_o - 10 \quad \text{db} \tag{2}$$

where

PWL = sound power level, db re 10^{-13} watts

$DI(\theta)$ = directivity index, db

d_o = reference distance from source, feet.

The directivity index for a directional source is the difference in db between the sound pressure level at a given point on a line having an angle, θ, with respect to some arbitrary axis of the source and the sound pressure level which would be produced at the same point by a non-directional source of the same acoustic power output.

The term, $20 \log (d/d_o)$, in Eq. (1) is the reduction in sound pressure level due to spherical divergence of the sound wave in spreading outward from the source, commonly referred to as "inverse square law attenuation." It is equivalent to a reduction of 6 db in sound pressure level for each successive doubling of distance from the source, or 20 db for each 10-times increase in distance.

The atmospheric attenuation, A, represents all reductions in sound pressure level over a given path of propagation in excess of the reduction due to the inverse square law attenuation. The two primary sources of energy loss are molecular absorption, due to humidity, and scattering of sound waves, due to inhomogeneity and turbulence in the atmosphere. In addition, for sources at very low angles of elevation the atmospheric attenuation may become very large due to the upward refraction of sound rays when propagated against the wind or in the presence of a strong temperature gradient over heated ground. It is convenient to separate the total atmospheric attenuation, A, into two components:

$$A = A_H + A_o$$

where

A_H = humidity attenuation

A_o = residual attenuation.

Procedures for predicting A_H and A_o are given in the following sections.

Humidity Attenuation, A_H

The attenuation of sound energy by molecular absorption is governed by absolute humidity, temperature, and frequency. Expressed as an attenuation coefficient, α_H, in db per 1000-ft. distance, the humidity attenuation may be computed from the formula:

$$\alpha_H = \frac{A_H}{d-d_o}$$

$$= \frac{0.1\, f\, (T + 45)}{f/h^2 + h^2/f} \tag{3}$$

where

d, d_o = distance in 1000 ft.

f = geometric mean frequency of an octave band in kilocycles

T = temperature, °F

h = absolute humidity, gm/m^3.

Charts of α_H plotted against absolute humidity and temperature for various octave frequency bands are given in Fig. 1. Absolute humidities may be converted to units of gm/m^3 from the units of grains/cu ft. more often given in meteorological data by multiplying the latter by 2.3. Also, absolute humidity in gm/m^3 is plotted in terms of dewpoint in °F in Fig. 2.

At low altitudes and in most weather conditions throughout the United States, the absolute humidity is high enough in relation to frequency (in kilocycles) that Eq. (3) may be simplified to:

$$\alpha_H = \frac{0.1\, (T + 45)\, f^2}{h^2} \tag{4}$$

This formula is valid for absolute humidities, h, greater than $(2f)^{1/2}$, where f is defined as before. The limiting value for h in the 1200-2400 cps band, which is usually the highest frequency range of interest for most airborne sources, is about 2 gm/m^3 (dewpoint of 12°F), and correspondingly less for lower frequencies.

In general, absolute humidity decreases considerably with altitude, and may reach low enough values to necessitate the use of the formula of Eq. (3) and the charts of Figs. 1 to 5. If the source is higher than a few thousand feet, and if data on temperature and humidity are available for various altitudes, it is advisable to compute the total humidity attenuation, A_H, from source to ground as the sum of the attenuations in successive layers of the atmosphere, i.e.,

$$A_H = A_{H_1} + A_{H_2} + \dots A_{H_k} + \dots$$

$$= \alpha_1 d_1 + \alpha_2 d_2 + \dots \alpha_k d_k + \dots$$

where α_k is the average attenuation coefficient given by the average temperature and humidity in the kth layer, and d_k is the distance over which the sound travels in that layer on the line between source and observer.

Residual Attenuation, A_o

Residual attenuation, A_o, defined as the atmospheric attenuation in excess of the humidity attenuation, A_H, is due principally to the scattering effects of air turbulence and to the formation of sound shadows by the upward refraction of rays near the surface of the earth. The latter situation produces quite large attenuations in comparison to those due to turbulence, but occurs in general only for source elevation angles of less than about 10° and in the presence of wind and temperature gradients which in combination result in a decrease of sound velocity with height. Residual attenuation due to turbulence rather than shadow formation will be discussed first.

Effects of Turbulence

Average values of residual attenuation, $\overline{A}_o$, due to turbulence, as determined from the experimental studies reported in Parts II and III, are plotted in Fig. 3 as a function of distance from the source and of source elevation angle. Data are shown for distances up to 5000 feet for source elevations of 2° to 90°. The dashed curves showing extensions of the distance range to 20,000 feet for source elevations of 30° to 90° are estimated from the limited data given in Part III.

For source elevations of 15° and higher, the variation of A_o with weather conditions from the average values shown by the curves is about ± 3 db. However, no significant correlation has been found between A_o and any measured weather variable.

For source elevations of less than 15°, the variation of A_o with weather is ± 5 to 8 db with respect to the average curves. Again, no significant correlation is found with weather variables, except for source elevations from 2° to 10° for the 75-150 cps frequency band, and for a 2° elevation for all frequencies. The principal weather variables affecting the attenuation, A_o, due to turbulence for these source elevations are wind velocity and temperature gradient. Their effects may be predicted by the formula:

$$A_o = \overline{A}_o - 0.3\, b_T\, (\Delta T + 4.5) + 0.12\, b_W\, (W - 9.5) \qquad (5)$$

where

A_o = predicted value of attenuation

$\overline{A}_o$ = average value given by curves of Fig. 3

ΔT = temperature gradient, °F per 1000-ft. height, measured between heights of 5 ft. and 500 ft.

W = wind speed, mph, averaged between ground and 500 ft.

The coefficients, b_T and b_W, are given in Table 1. The temperature gradient, ΔT, is taken as positive for a temperature at 5 feet higher than at 500 feet. The choice of the 5-foot height is critical because of the pronounced variation of temperature with height near the ground.

Deviation of individual values of A_o from those predicted by the above procedure will usually be within about ± 4 db.

Effects of Sound Shadows

The values of attenuation, A_o, obtained by the foregoing procedure are those which are to be expected when the observation point is not in a sound shadow. The prediction of attenuation within shadow zones will be discussed in the following paragraphs.

The sound velocity in a given horizontal direction in the atmosphere depends both on the temperature and on the vector addition of the component of wind velocity in that direction. The sound velocity, c, is given by the expression:

$$c = c_T + c_W$$

TABLE I

Coefficients for Prediction of Attenuation, A_o, Due to Turbulence

Source Elevation	Distance from Source, ft.	75-150 b_T	75-150 b_W	150-300 b_T	150-300 b_W	300-600 b_T	300-600 b_W	600-1200		1200-2400	
2^o	1000	-2.5	4.8	-1.2	1.2	0.0	0.0	-0.5	2.6	-1.2	0.4
	2000	-1.5	4.4	-1.2	1.3	0.9	0.0	-0.6	3.9	-1.4	0.0
	3000			-1.2	0.0	1.7	0.0	-1.1	4.4		
	4000							-2.0	4.0		
5^o	1000	-0.7	2.4	*	*	*	*	*	*	*	*
	2000	-1.0	1.5	*	*	*	*	*	*	*	*
10^o	1000	1.2	-1.7	*	*	*	*	*	*	*	*
	2000	0.2	-1.6	*	*	*	*	*	*	*	*

Frequency Band spans the 75-150 through 1200-2400 columns.

* No significant correlation

where c_T is the sound velocity determined by temperature alone at the given point, $c_W = W \cos \phi$ is the component of wind speed, W, in the direction of sound propagation, and ϕ is the angle between the wind direction and the direction of sound propagation, or "wind-sound" angle. Sound propagation in directions for which $c_W = W \cos \phi$ is positive is referred to as "downwind" propagation, and "upwind" for negative c_W.

When the variation of c_T and c_W with height is such that the net sound velocity, c, decreases with height, sound rays will be refracted upward, as shown in Fig. 4. It is seen that the ray which is tangent to the ground defines the boundary of a sound shadow. If the shadow were perfect, no sound energy would be observed in the shadow zone. However, a small amount of sound does cross the shadow boundary due to diffraction and scattering, resulting in highly attenuated levels in the shadow zone.

In order to estimate the residual attenuation, A_o, due to shadow formation it is necessary first to know whether or not the observation point is within the shadow zone. This can be determined from Fig. 5 in which the horizontal distance from the source to a point on the shadow boundary 5 feet above the surface is plotted as a function of source height and the logarithmic sound velocity gradient B[1].* Experimental data[2,3] indicates that the wind speed is more nearly proportional to the logarithm of the height than to the height directly, up to a few hundred feet. The same is usually true of the temperature[2,3] and the temperature-dependent sound velocity, c_T. The logarithmic gradient, B, is defined by the following relationships:

$$c = c_o \left(1 + B \log_e \frac{z}{z_o}\right)$$

$$c_T = c_{o_T} \left(1 + B_T \log_e \frac{z}{z_o}\right)$$

$$c_W = c_{o_W} \left(1 + B_W \log_e \frac{z}{z_o}\right)$$

$$B = B_T + B_W$$

where $c_o = c_{o_T} + c_{o_W}$ is the sound velocity at a reference height, z_o, and $c = c_T + c_W$ is the velocity at height, z.

The value of B_T is given approximately by:

$$B_T = 4 K \times 10^{-4} \qquad (6)$$

* References are designated by superscripts.

where

$$K = \frac{T - T_o}{\log_{10} (z/z_o)} \ {}^{\circ}F$$

If the ratio, z/z_o, is chosen as 10, then:

$$B_T = 4 (T - T_o) \times 10^{-4} \ {}^{\circ}F \tag{7}$$

The gradient, B_W, due to wind is found experimentally to be approximately proportional to the wind speed component at a given height. If the height is taken as 30 feet, the value of B_W is approximately:

$$B_W = 1.5 \, W_{30} \cos \phi \times 10^{-4} \tag{8}$$

where W_{30} is in miles per hour. The wind speed at 30 feet may be estimated from the known speed, W_z, at any other height (up to about 300 feet) by the relation:

$$W_{30} = \frac{W_z}{1 + 0.27 \log_{10} (z/30)} \quad \text{miles per hour} \tag{9}$$

The gradient, B_T, may be either positive or negative, depending on whether the temperature increases or decreases with height. Scalar wind speed always increases with height, but its component, $W \cos \phi$, and consequently the gradient, B_W, may be positive or negative depending on whether sound propagation is downwind or upwind. Shadow formation will usually occur, therefore, only for upwind propagation, and for downwind propagation only under conditions where a strong negative temperature gradient more than counteracts a weak wind component. In the absence of wind, shadow formation will occur only with a negative temperature gradient.

Representative maximum values of B resulting from combined negative temperature and wind gradients are of the order of -0.005. As seen in Fig. 5, this would cause the observation point to lie in the shadow zone for any source elevation angle of less than about 10°. It will be noted also that the other gradients shown in Fig. 5 correspond fairly closely to specific source elevation angles and that the larger the gradient, the higher is the source elevation below which a shadow will be formed.

As the observation point moves into the shadow zone away from the boundary, the residual attenuation, A_o, first increases rapidly and then attains a limiting value at which it remains essentially constant*. Available data are not adequate to permit an exact prediction of this limiting value, but it is generally within the range of 25 to 35 db. This includes residual attenuation due to turbulence within the shadow zone. No significant relation of the limiting value of attenuation to weather variables or to frequency has been found. For lack of more complete data, the limiting value of shadow attenuation may therefore be estimated as 30 db $\pm$ 5 db, subject to the condition for the wind-sound angle, ϕ:

$$\phi \geqq \phi_c + 60° \qquad \phi \text{ and } \phi_c \text{ between } 0° \text{ and } 180°$$

$$\phi \leqq \phi_c - 60° \qquad \phi \text{ and } \phi_c \text{ between } 180° \text{ and } 360°$$

where

$$\phi_c = \cos^{-1} \frac{-B_T}{1.5\, W \times 10^{-4}}$$

The critical angle, ϕ_c, is that at which the wind dependent sound velocity gradient, B_W, and the temperature dependent velocity gradient, B_T, are equal and opposite, and is the wind-sound angle below which no shadow formation occurs. For zero temperature gradient, the critical angle, ϕ_c, would be 90° and 270°, measured from the direction in which the wind is blowing. For a negative temperature gradient, the critical angle would be less than 90° and greater than 270°, indicating that shadow formation could occur for downwind propagation.

As the difference between ϕ and ϕ_c becomes less than 60°, the limiting value of attenuation decreases and approaches the values given for non-shadow propagation in Fig. 3.

The distance from the shadow boundary at which the shadow attenuation reaches the limiting value is also difficult to predict exactly. For wind-sound angles between 110° and 250°, this distance may be taken as three times the distance from the source to the shadow boundary. For wind-sound angles outside this range the distance becomes much larger.

* The discussion of shadow attenuation comes mainly from Wiener and Keast.[3]

SECTION III

SUMMARY

The steps to be followed in predicting the sound pressure level on the ground (at 5 ft height) at each octave frequency band due to an airborne source are:

1. Determine SPL_o at reference distance, d_o, from directly measured data, or from power level and directivity index data using Eq. (2).

2. Determine source elevation angle, β, from source height, z, and horizontal distance, r, or slant distance, d, from source to receiver, using:

$$\beta = \tan^{-1} \frac{z}{r} = \sin^{-1} \frac{z}{d}$$

3. Obtain the following weather data:

(a) Temperature, T, in °F at heights of 5, 50, and 500 feet and at available intervals up to source altitude.

(b) Absolute humidity, h, in gm/m^3 at 5 feet height and at available intervals up to source altitude. Convert dewpoint, °F, to absolute humidity using curve of Fig. 2.

(c) Wind speed, W_{30}, in miles per hour and direction at 30 feet height. If speed is measured at any other height between 5 and 300 feet, compute W_{30} from Eq. (9). Measure the wind-sound angle, ϕ, between the direction toward which the wind is blowing and the direction in which sound is propagated from source to observation point.

(d) Wind speed averaged between ground and 500 feet. This is most conveniently determined from the elevation angle of a weather balloon at approximately this altitude.

4. Compute humidity attenuation, $A_H = \alpha_H (d-d_o)$, from the data in 3(a) and 3(b), using Eq. (3) or the curves of α_H given in Fig. 1. If h is greater than $(2f)^{1/2}$ where f is frequency in kilocycles, use Eq. (4). If the source height is greater than 2000 feet, compute A_H by layers to account for the variation of h and T with height.

5. Determine whether or not the ground observation point is in a sound shadow, using Fig. 5. If the horizontal distance, r, from source to receiver is greater than the distance, R_o, for a given source height and value of sound velocity gradient, B, then the observation point will be in a shadow.

(a) Determine $B = B_T + B_W$ from Eqs. (6) and (8). If temperatures at heights of 5' and 50' are available from 3(a), use Eq. (7) for determining B_T. Otherwise, use any two temperatures between 3 and 300 feet with Eq. (6).

6. If observation point is not in a sound shadow, determine average residual attenuation, $\overline{A}_o$, from slant distance, d, and source elevation angle, using Fig. 3.

(a) If source elevation is 2° or less for any frequency, or 10° or less for the 75-150 cps octave band, correct the value of A_o given by the curves of Fig. 3 by applying Eq. (5) and Table 1, using the temperature and wind data from 3(a) and 3(d).

7. If observation point is in sound shadow, for wind-sound angles between 110° and 150°, and its horizontal distance, r, from the source is more than three times the horizontal distance, R_o, from source to shadow boundary, use a value of 30 db for residual attenuation, A_o.

(a) If r is less than 3 R_o, determine A_o at the distance, R_o, as in 6 and 6(a), and add an amount, ΔA_o, given by

$$\Delta A_o = \frac{(r - R_o)(30 - A_o)}{2 R_o} \quad \text{db}$$

8. Determine the sound pressure level at the ground observation point from Eq. (1), using $A = A_o + A_H$.

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3. Wiener, F. M., and D. N. Keast, "Experimental Study of the Propagation of Sound Over Ground," Journal of the Acoustical Society of America, Vol 31, pp 724-733, June 1959.

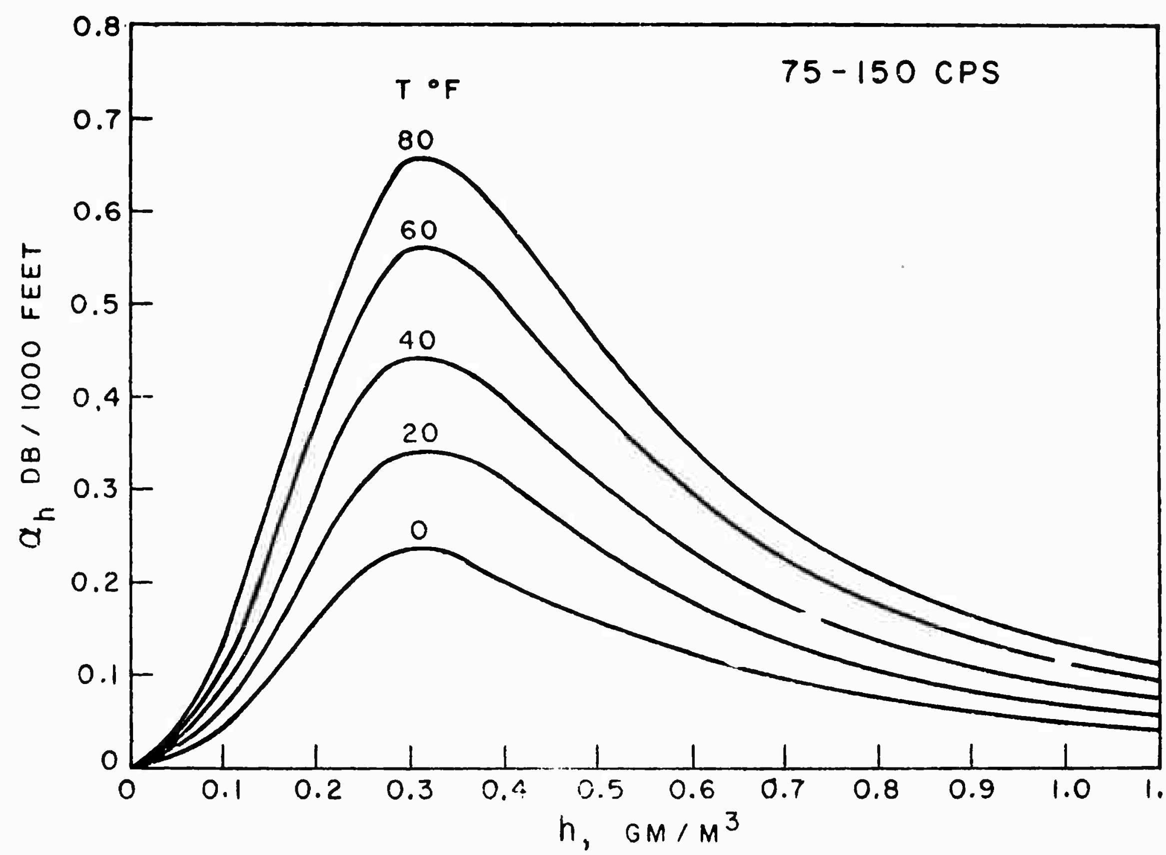

Fig. 1 A - Relation of Humidity Attenuation Coefficient, α_H, to Temperature, T, and Absolute Humidity, h. 75-150 cps

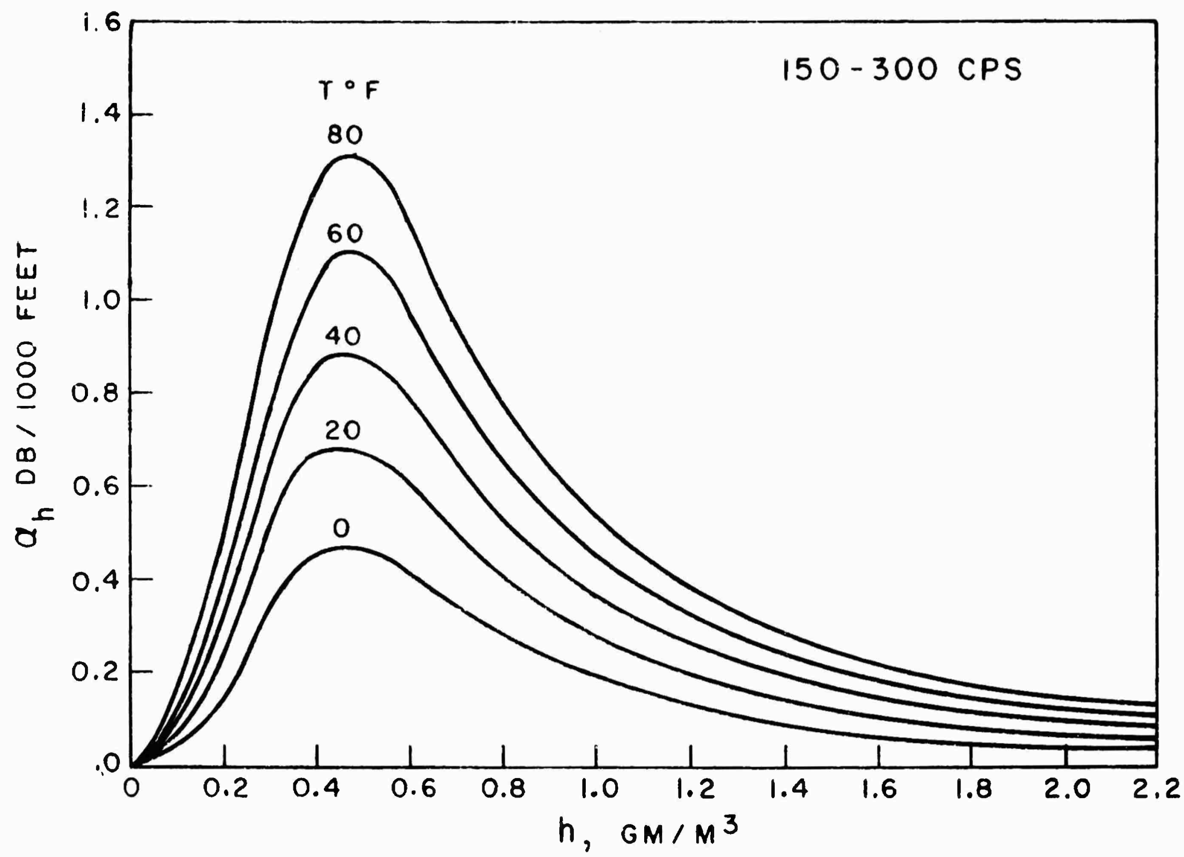

Fig. 1-B - 150-300 cps

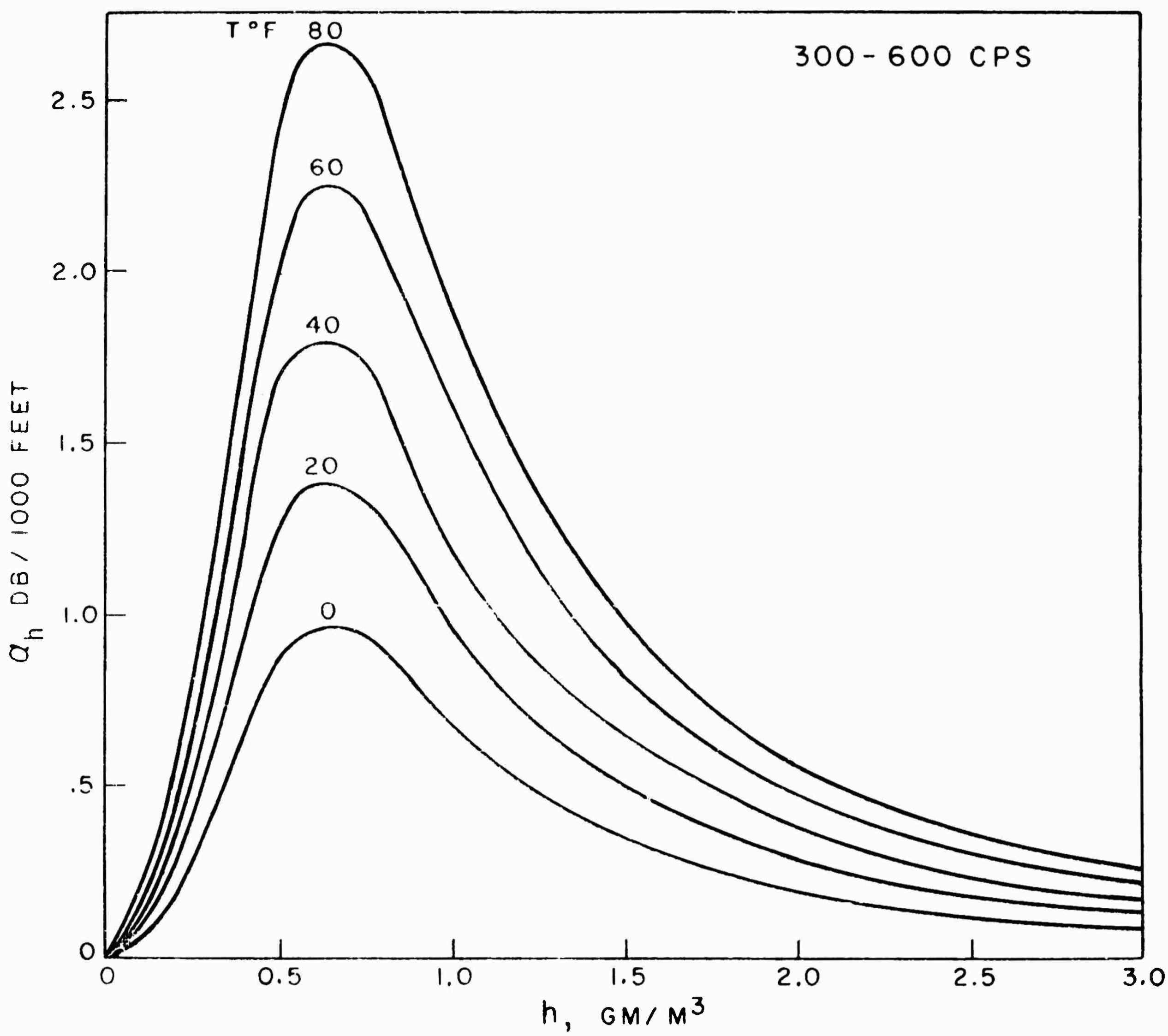

Fig. 1-C - 300-600 cps

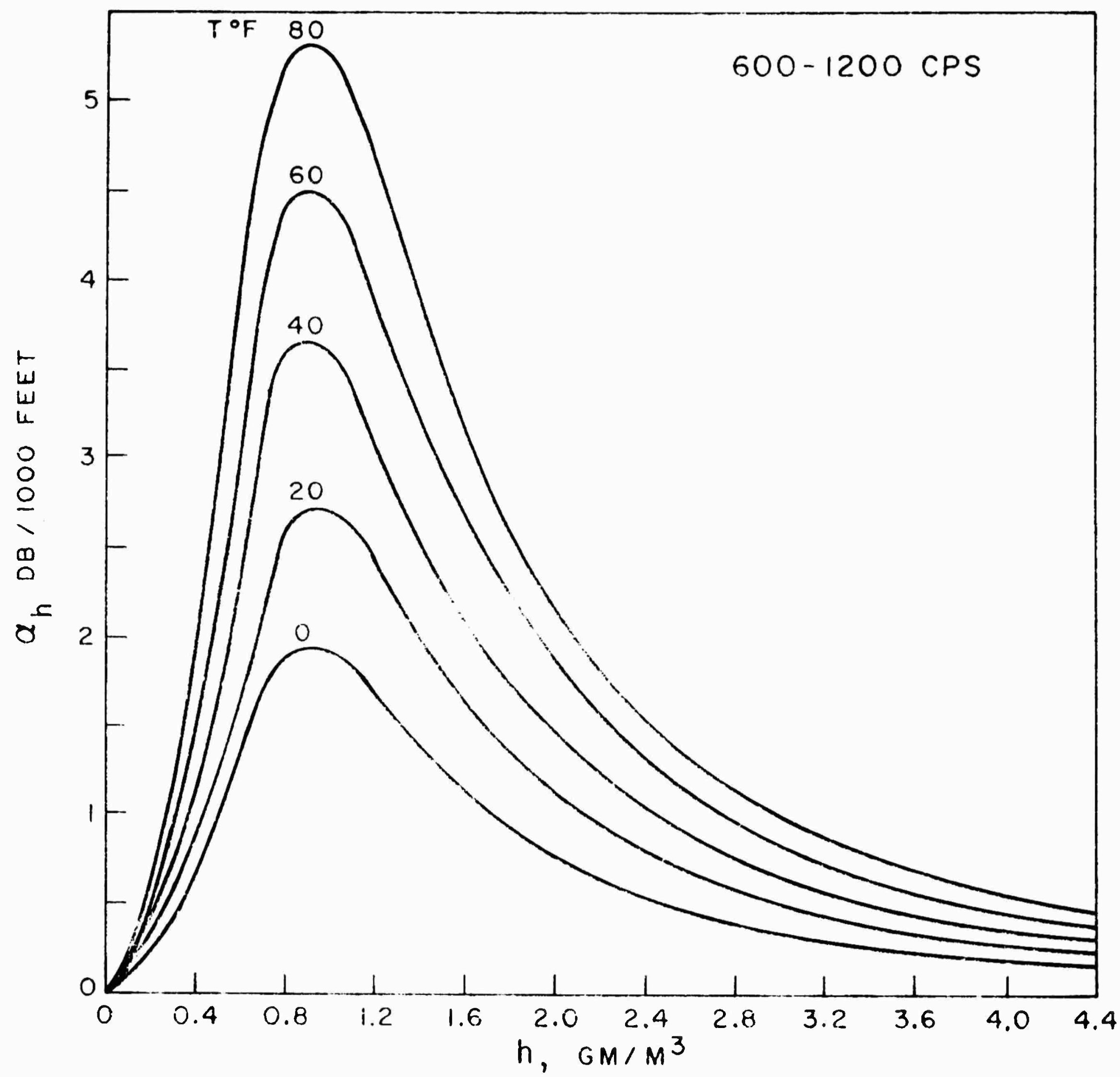

Fig. 1 D - 600-1200 cps

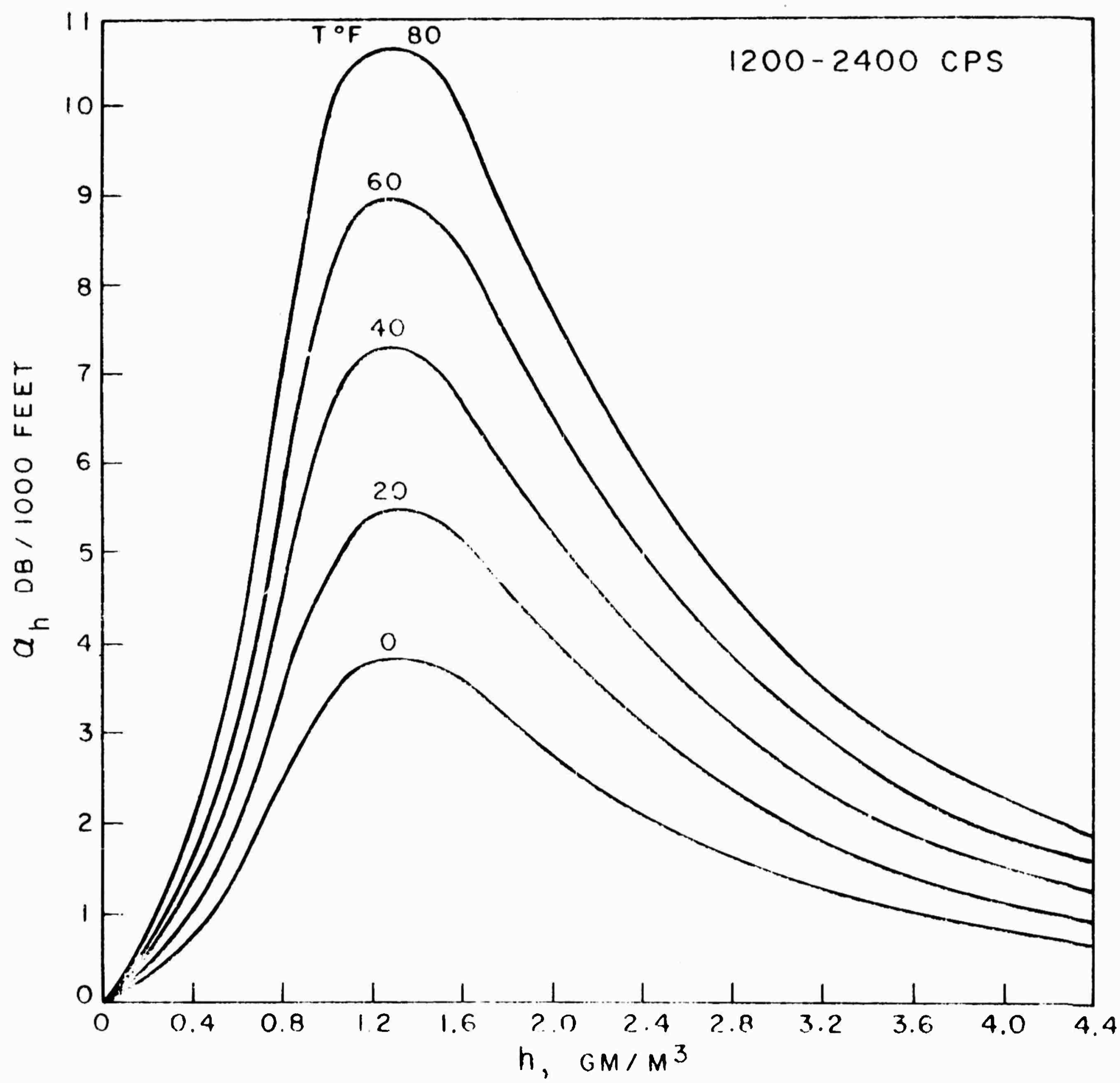

Fig. 1-E - 1200-2400 cps

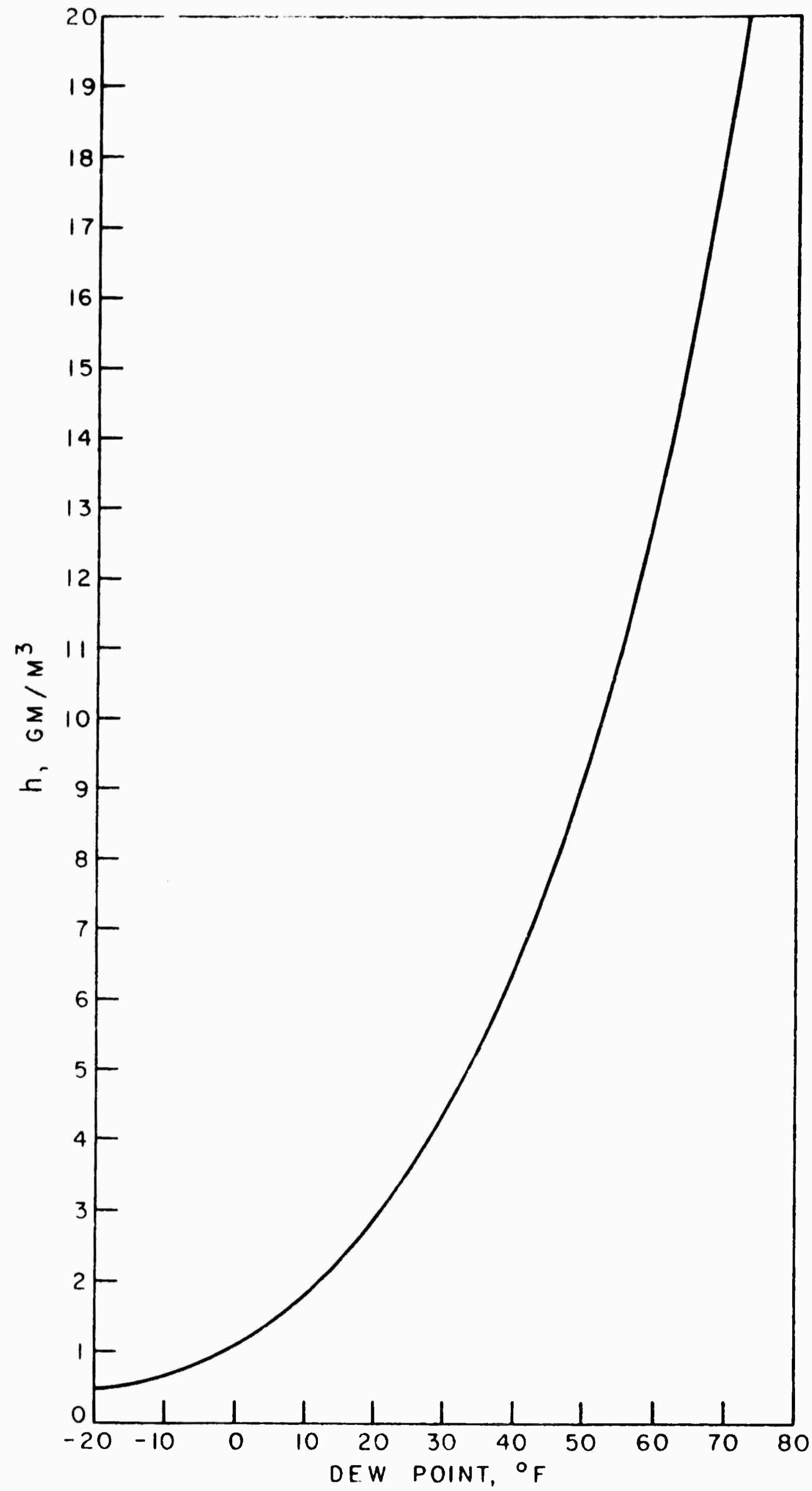

Fig. 2 - Relation of Absolute Humidity, h, to Dewpoint, °F

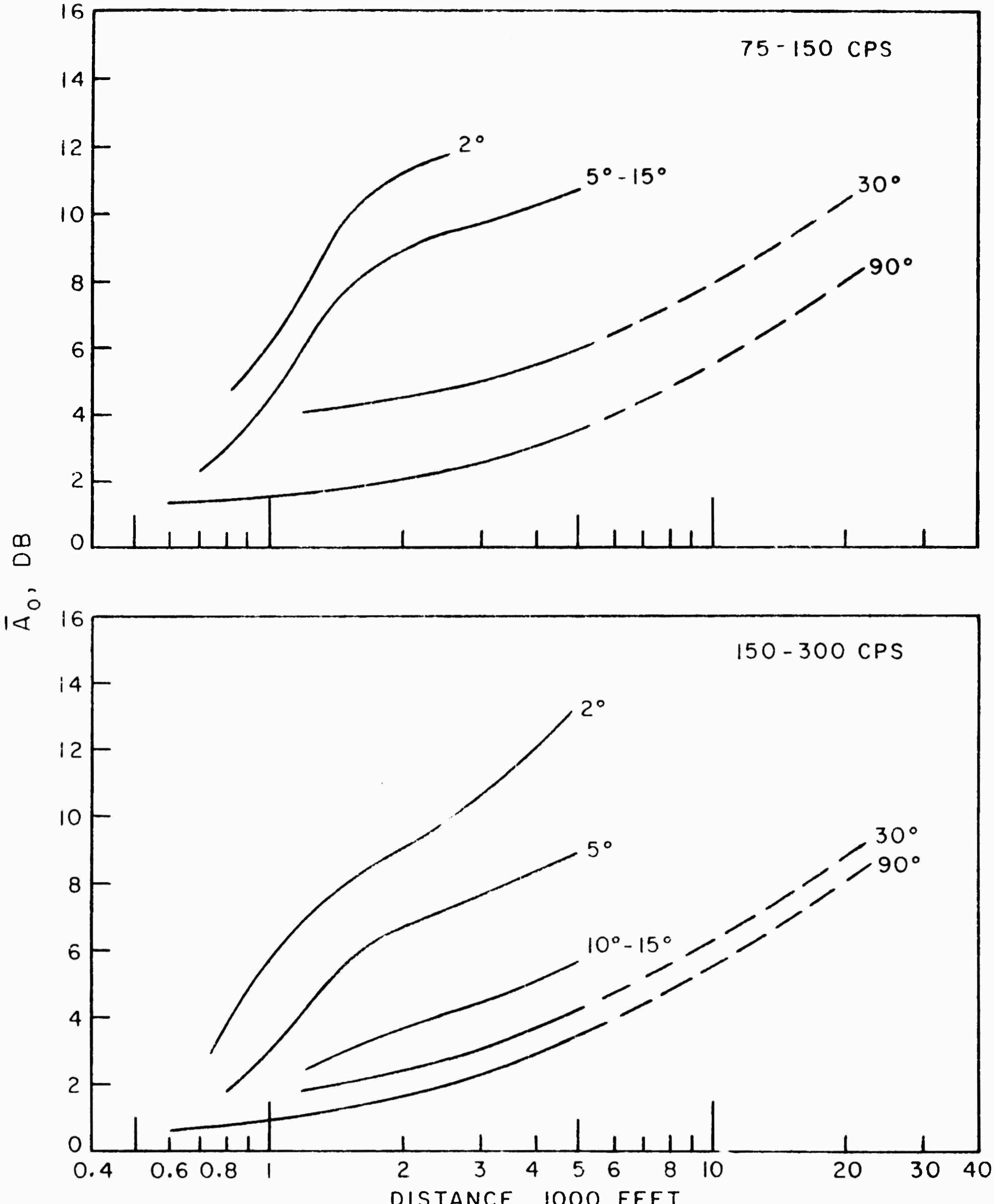

Fig. 3-A - Average Residual Attenuation, $\bar{A}_o$, Due to Turbulence, as a Function of Distance from Source and Source Elevation Angle. 75-300 cps

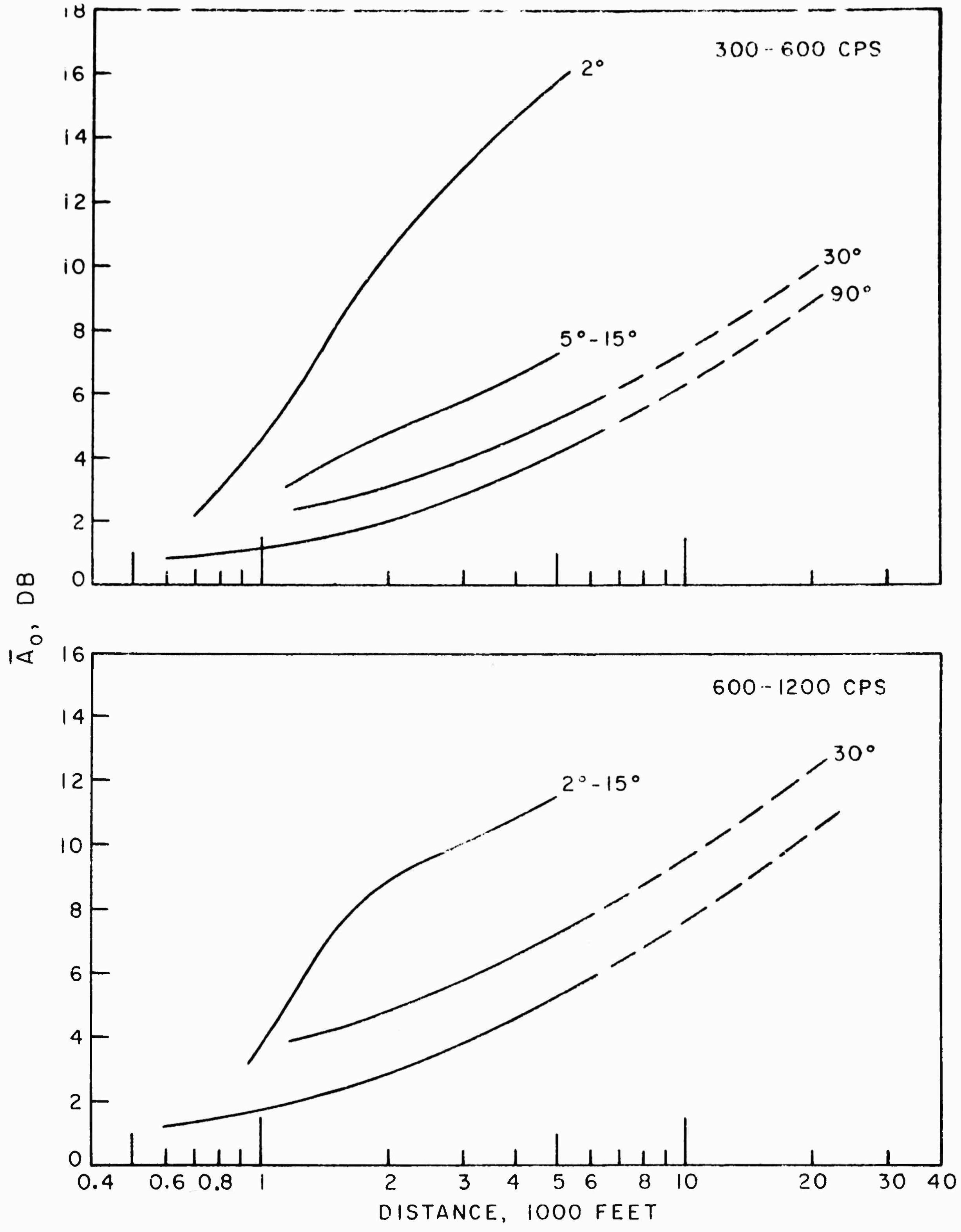

Fig. 3-B - 300-1200 cps

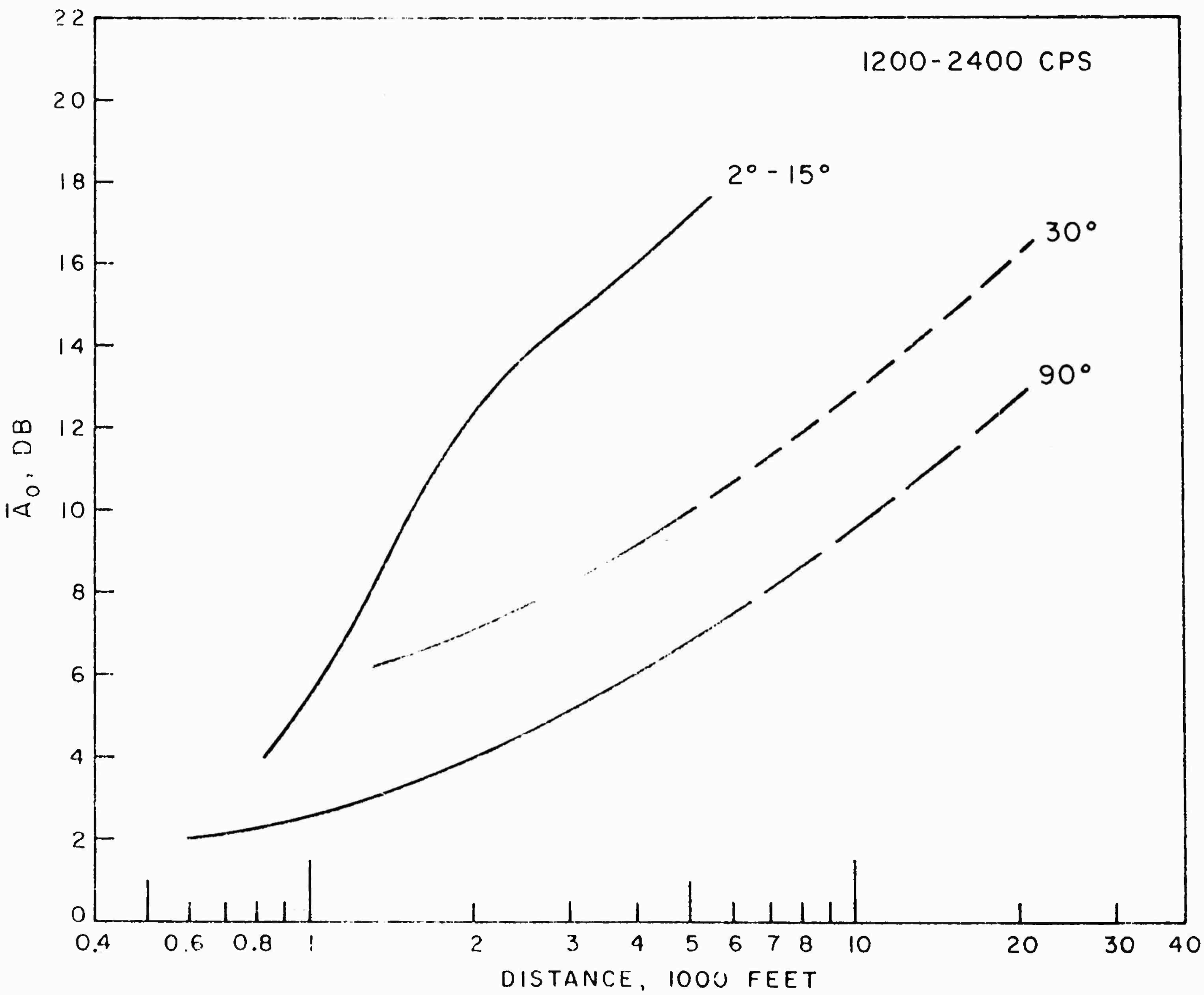

Fig. 3-C - 1200-2400 cps

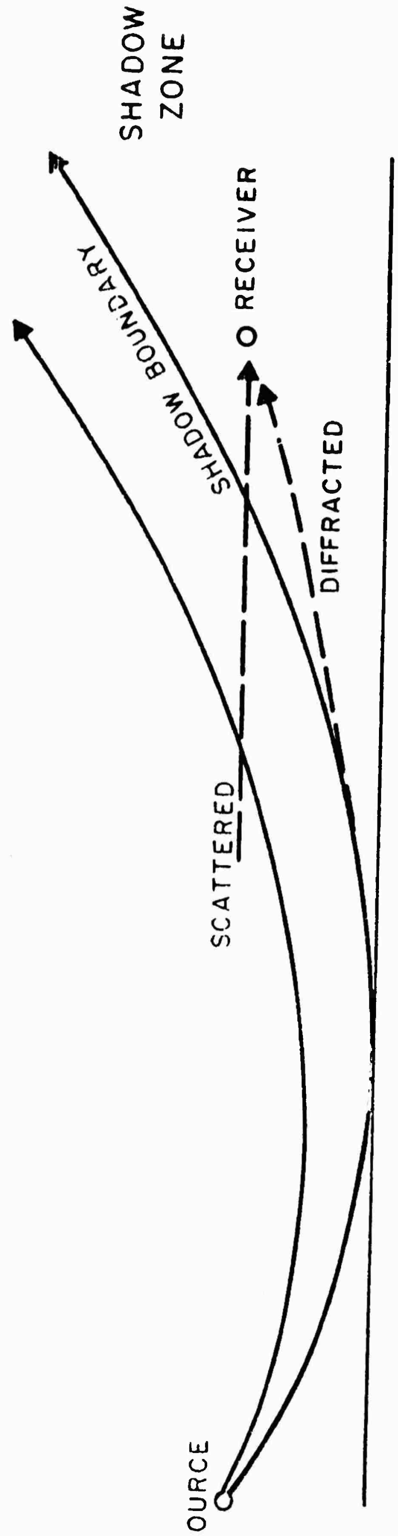

Fig. 4 - Diffraction and Scattering of Sound into Shadow Zone

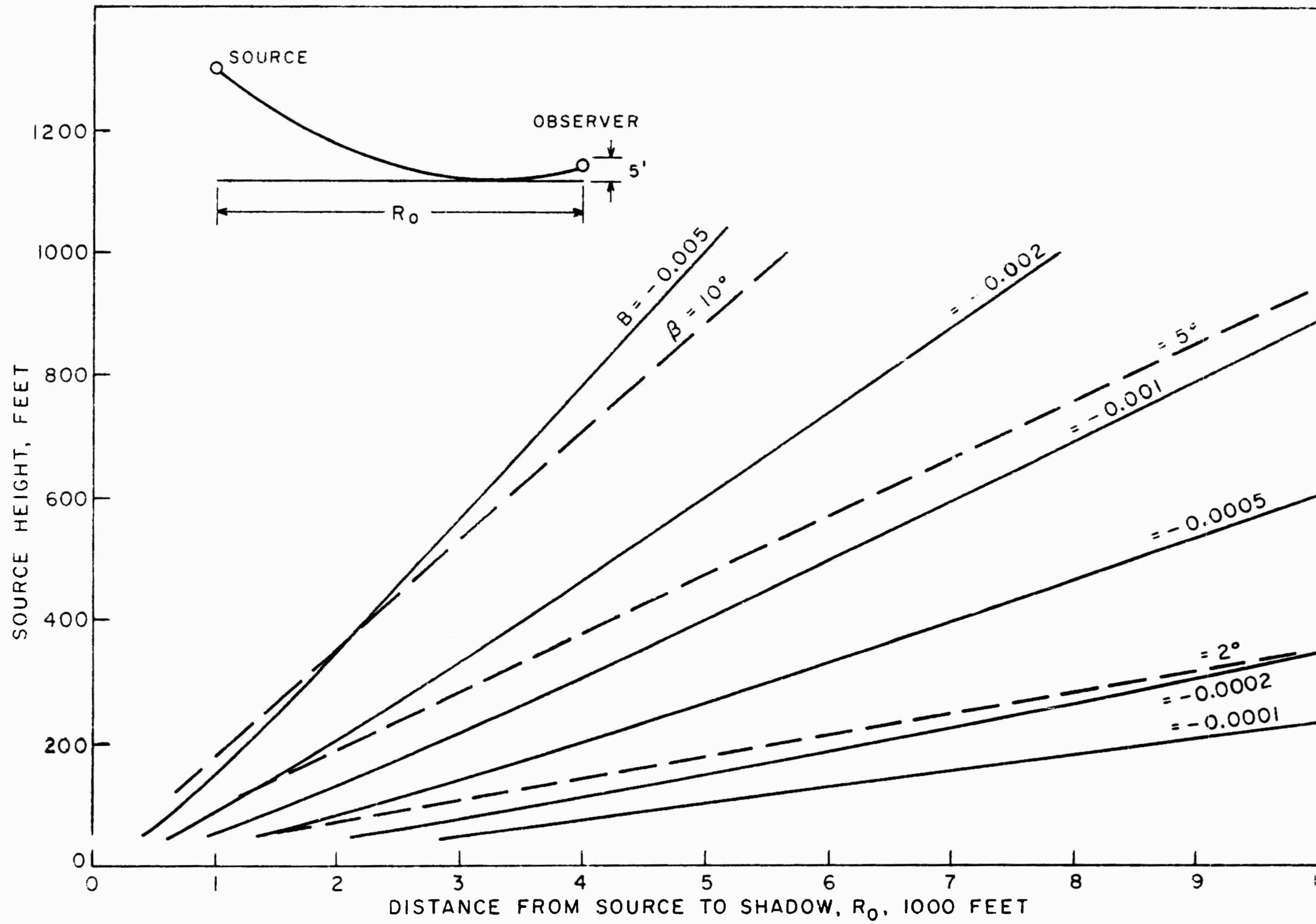

Fig. 5 - Horizontal Distance, R_o, from Source to Shadow Boundary as a Function of Source Height and Logarithmic Sound Velocity Gradient B. Height of Observation Point, 5 ft. Source Elevation Angles, β, Shown for Comparison